CONE PENETRATION TESTING AND SITE EXPLORATION IN EVALUATING THE LIQUEFACTION RESISTANCE OF SANDS AND SILTY SANDS

E. J. Newman[1], T. D. Stark[2], and S. M. Olson[3]

ABSTRACT

Refined relationships between cone penetration tip resistance and liquefaction resistance of sandy soils are presented to facilitate use of the cone penetration test (CPT) in liquefaction studies. The proposed relationships are based on a database of field case histories where CPTs were performed and adjacent borings were drilled and sampled to confirm soil type and fines content. The newly-developed database employs stringent selection criteria to minimize inconsistencies in CPT sounding selection and interpretation that are present in other level-ground liquefaction databases, as well as to aid in the addition of data by others. Applying these proposed stringent criteria results in a reduced, but more defensible, database. Additionally, the effect of fines content on liquefaction resistance is quantified by a fines content adjustment in a form that facilitates use in practice.

Introduction

Both the cone penetration test (CPT) and the standard penetration test (SPT) offer advantages and disadvantages in estimating soil properties. The cone penetration test is more economical, allowing practitioners to perform more tests and to gain a better understanding of soil property variability at a site. The continuous profile measured by the CPT reduces uncertainty associated with potential thin layers that may or may not be discovered and sampled when using a conventional sampling interval for the SPT. A disadvantage of the CPT is that commonly used equipment does not retrieve a soil sample for examination or laboratory testing, although considerable empirical data exist to correlate CPT measurements to various soil properties (e.g., Meigh 1987, Kulhawy and Mayne 1990, Lunne et al. 1997). The standard penetration test retrieves a soil sample during the test and, if coordinated with a CPT program, can greatly enhance the CPT data interpretation.

To facilitate use of the CPT in level-ground liquefaction analyses, numerous investigators have proposed relationships between liquefaction resistance and CPT measurements (e.g. Stark

[1] Graduate research assistant, Dept. of Civil and Environmental Engineering, University of Illinois at Urbana-Champaign, Urbana, IL 61801
[2] Professor, Dept. of Civil and Environmental Engineering, University of Illinois at Urbana-Champaign, Urbana, IL 61801
[3] Assistant Professor, Dept. of Civil and Environmental Engineering, University of Illinois at Urbana-Champaign, Urbana, IL 61801

and Olson 1995, Suzuki et al. 1997, Robertson and Wride 1998). The work discussed herein applies to level- or mildly sloping ground liquefaction only; for brevity the term “liquefaction” will be used throughout.

In this paper, the authors propose a consistent set of criteria to use in selecting data from liquefaction cases and then apply these criteria to develop an improved database of liquefaction and non-liquefaction cases. Using the improved database, the authors propose new relationships for evaluating liquefaction resistance of sandy soils and an adjustment to the CPT tip resistance to estimate numerically the liquefaction resistance of sandy soils containing fines.

Evaluating Liquefaction Potential

Seed and Idriss (1971) proposed a method of estimating the magnitude of earthquake-induced shear stresses in a natural soil deposit. These seismically-induced shear stresses are compared to the liquefaction resistance of a soil to evaluate triggering of liquefaction. Because of the complexity of the behavior of natural soils and the difficulties and cost involved in sampling and laboratory testing of sandy soils in the laboratory, insitu testing is an ideal method to empirically estimate the liquefaction resistance of natural soil deposits. This study utilizes CPT tip resistance for this purpose. The seismic shear stress ratio (SSR) is calculated as described by Seed and Idriss (1971) and Youd et al. (2001) from the peak ground acceleration and initial vertical total and effective stresses at a site and is adjusted for depth and earthquake magnitude using the factors recommended by Youd et al. (2001).

CPT-Based Case Histories to Estimate Liquefaction Resistance

Olson and Stark (1998) present three liquefaction resistance relationships for sandy soils with varying fines content and median grain diameter. They confirm similar findings by other investigators that liquefaction resistance of sandy soils varies significantly with fines content, especially for soils with fines contents less than 35%. Robertson and Wride (1998) (updating the work of Robertson and Campanella (1985)) present a liquefaction resistance relationship for clean sands and a method for adjusting measured penetration resistance to an equivalent clean sand value. The adjustment proposed by Robertson and Wride (1998) relies on both sleeve friction measurements and cone tip resistance to estimate soil type behavior. Due to the large amount of variability observed in this adjustment (Newman et al. 2006), the liquefaction resistance curves developed herein utilize fines content measured in soil samples taken from an exploratory borings in conjunction with CPT measurements.

Update of CPT Liquefaction Resistance Database

In this study, the authors re-examine each case history in the Olson and Stark (1998) database in light of the newly-proposed selection criteria described herein. In addition, the authors collected and analyzed data from more recent earthquakes. To reduce potential biases or inconsistencies in the data selection process for the case history database, the following stringent selection criteria are proposed:

1. There must be an adjacent SPT boring (with available log) to confirm interpreted soil stratigraphy from the CPT;
2. Fines content must be measured in a soil sample retrieved from the layer under

consideration in the adjacent SPT boring; and

3. Other data at the site must indicate that the selected measurements are representative of the soil conditions that existed to initiate liquefaction at the site.

Furthermore, when considering multiple CPT soundings available in one liquefied area, the CPT measurement (and corresponding fines content) that best represents the nature of the soil where liquefaction is thought to have initiated is chosen. Thus, only one liquefaction data point is used at each site. All available information from CPT and SPT logs at the site should be considered in determining whether to assign a measured fines content to a measured q_{c1} value. Even carefully considering these factors, there is still some variability expected with respect to fines content in the resulting liquefaction resistance relationships. More than one data point from a group of soundings is used only if the soil layer has a range of fines contents and corresponding q_{c1} values and it is not possible to identify which pair of q_{c1} and fines content values best characterize the soil in the layer at which liquefaction was initiated at a site. This is commonly the situation in cases where the fines content of the soil is greater than 35%.

The representative q_{c1} value is calculated over a 0.75 m interval, which is consistent with the minimum thickness of the strata that is usually the source of significant deformations (Boulanger et al. 1997). In situations where q_{c1} changes with depth in a layer and more than one fines content measurement is available in the liquefied layer, the pair of q_{c1} and fines content most likely to represent the nature of the soil where liquefaction initiated was chosen. If necessary, the data for each pair can be plotted with existing liquefaction resistance relationships to help define what combination of q_{c1} and fines content represents the "most liquefiable" condition.

Liquefaction Resistance of Sandy Soils

Stark and Olson (1995) utilized three soil type groups to characterize liquefaction resistance. These groups are delineated using fines content and D_{50}. Stark and Olson (1995) used the median grain diameter, D_{50} for soil classification where fines content was not available. Because the new selection criteria require a reliable value of fines content, the median grain size is omitted from the soil groupings presented herein.

The three soil type groups used by Stark and Olson (1995) and Olson and Stark (1998) to characterize liquefaction resistance are clean sand, silty sand, and silty sand-sandy silt, corresponding to fines contents of less than or equal to 5%, between 5 and 35%, and greater than or equal to 35%, respectively. Applying these liquefaction resistance relationships has been somewhat problematic because of the large range of fines content for the silty sand group (5 to 35%). In general, soils with a fines content greater than 35% often exhibit apparently high liquefaction resistance and thus the large range of fines contents for the silty sand-sandy silt group (> 35%) does not appear critical. However, the large fines content range for the silty sand group, 5 to 35%, is significant because this range encompasses a wide range of natural soils and q_{c1} values (about 5 to 12 MPa) that are liquefiable. Thus, one objective of this study was to clarify the empirical liquefaction resistance of silty sands.

To clarify the effect of fines content on liquefaction resistance, the authors propose four ranges (or groups) of fines contents (FC; in percent): (1) FC < 12; (2) 12 ≤ FC < 20; (3) 20 ≤ FC

< 35; and (4) FC ≥ 35. The Unified Soil Classification System (USCS) (ASTM D2487-98) defines "sands with fines" as sands with fines contents of more than 12%, while a clean sand is defined in the USCS as a sand with less than 5%. Thus a fines content between 5 and 12% is a transition zone between clean sand and sand with fines in the USCS. However, this study found no clear increase in liquefaction resistance for sands with fines contents between 5 and 12%. Therefore, the "sands with transitional fines contents" (5 < FC <12) were grouped with "clean sands" for this study. The value of FC = 20 for the third group was selected arbitrarily based on the distribution of fines contents in the database cases. Because the median grain size and the soil type descriptions (clean sand, silty sand, and silty sand-sandy silt) used in Stark and Olson (1995) are not relevant to the new liquefaction resistance relationships, the new groups are defined using only fines content and identified by a "Soil Group Number", namely, Soil Groups 1 through 4. Newman et al. (2006) present the full database, as well as a detailed review of the cases and the development of the various soil groups and corresponding liquefaction resistance relationships.

Proposed Liquefaction Resistance Relationships

Figure 1 presents the proposed liquefaction resistance relationships for the four Soil Groups. The proposed liquefaction resistance relationships in Figure 1 constitute a liquefaction assessment chart that can be used to estimate the factor of safety against liquefaction for sandy soils subjected to a M7.5 earthquake, level ground or mildly sloping ground conditions, and fines contents ranging from zero to greater than 35%. Factors recommended by Youd et al. (2001) can be used to adjust values of liquefaction resistance for other earthquake magnitudes and effective overburden stresses greater than 100 kPa.

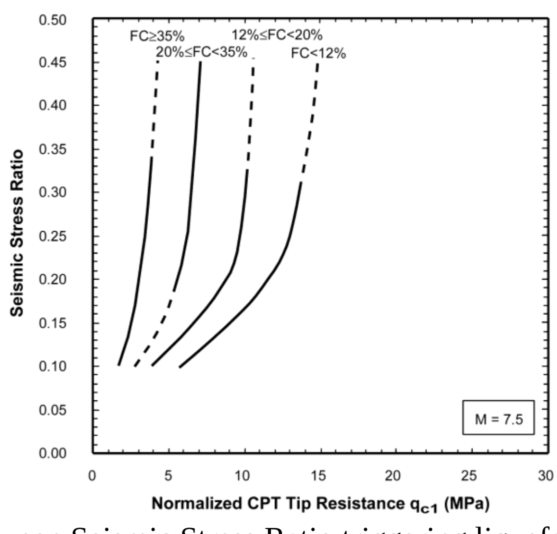

Figure 1. Relationship between Seismic Stress Ratio triggering liquefaction and q_{c1} values for all four soil type groups and M=7.5 earthquakes.

The main disadvantage of the liquefaction relationships in Figure 1, and thus the use of the CPT in liquefaction assessments, is that an estimate of fines content is required. As discussed previously, it is possible to estimate soil type and fines content from soil classification charts, e.g., Robertson and Wride (1998), using CPT measurements. However, because of the uncertainties in estimating soil type from CPT results alone, the authors recommended that the

CPT be used to delineate zones and/or seams of potentially liquefiable soils. In zones of potential liquefaction, a sample and blowcount(s) should be obtained to measure fines content, confirm soil stratigraphy, and verify liquefaction resistance. This combination of CPTs and one or more borings has been used in practice for many years, and thus should not significantly increase the cost of a site investigation (Stark and Olson 1995).

Fines Content Adjustment

To facilitate the use of the proposed relationship and to compare the data for fines contents other than those corresponding to the boundaries in Figure 1, an adjustment (similar to the fines content adjustment factor used in the SPT-based liquefaction resistance relationship from Youd et al. (2001)) based on measured fines content can be developed using the four curves in Figure 1. Comparing the values of q_{c1} for Soil Groups 2-4 to the value of q_{c1} corresponding to Soil Group 1 at a constant SSR yields a ratio of penetration resistance at the given fines content to the penetration resistance of a clean sand. Repeating this exercise for a number of SSR values yields the average ratios and ranges plotted Figure 2 as a function of fines content. This ratio is the factor by which a measured q_{c1} for a soil with a particular fines content can be multiplied to yield an "equivalent" q_{c1}-value in a clean sand. Also plotted in Figure 2 is the relationship between the soil type adjustment factor and fines content from Robertson and Wride (1998) using their approximate relationship between fines content and soil type as determined from CPT tip resistance and sleeve friction.

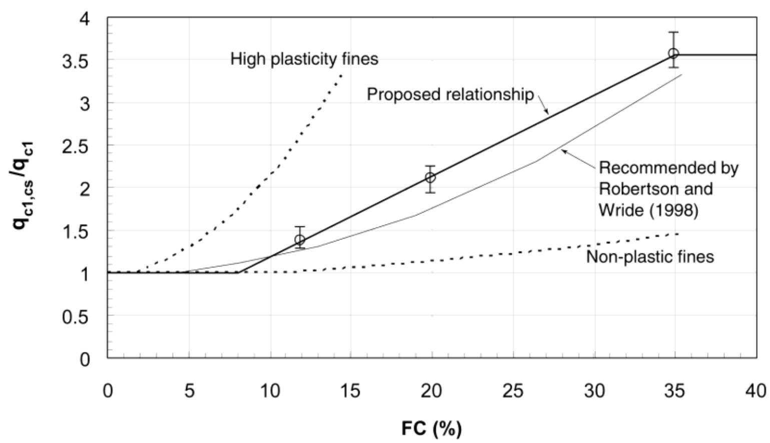

Figure 2. Comparison between proposed fines content correction and approximate fines content correction from Robertson and Wride (1998) with upper and lower bounds

The proposed adjustment is conservatively capped at a fines content of 35% with $q_{c1cs}/q_{c1} = 3.55$. The adjustment factor is set equal to one at fines contents less than 8%. This is in agreement with laboratory data reported by Ishihara (1993) that suggest small amounts of non-plastic fines have little to no effect on cyclic resistance alone (i.e., in the laboratory) as well as the generalities of the USCS classification system which suggests a transition from clean sand to silty sand behavior at fines contents between 5 and 12%.

The proposed FC adjustment shown in Figure 2 can be described and applied using the following equations:

$$C_{FC} = 0.095 \cdot FC + 0.22 \qquad 8 < \text{FC} < 35\% \tag{1}$$

$$q_{c1,cs} = C_{FC} \cdot q_{c1} \tag{2}$$

where C_{FC} is the fines content adjustment factor, and $q_{c1,cs}$ is the equivalent clean sand penetration resistance (in MPa) corresponding to a particular fines content.

If this fines content adjustment is applied to all cases in the updated database, the adjusted data can be compared to the proposed Soil Group 1 relationship to determine if the spacing and interpolation among the four curves is reasonable. Figure 3(a) shows the data in the updated database adjusted for fines content using the relationship proposed above and plotted with the Soil Group 1 curve (i.e., the "base curve"). Of these cases, 8 of the 117 (7%) are misclassified. The eight liquefaction cases that are overadjusted lie to the right of the base curve. The base curve does a reasonable job of separating the liquefaction points from the no liquefaction points; all of the no liquefaction cases lie on or to the right of the base curve. Of the four Soil Type Groups, adjusted data from each of them is located near the base curve. This implies that the proposed fines content adjustment is reasonable over the entire range of fines contents in the database.

For comparison, Figure 3(b) plots the 88 cases in the updated database for which sleeve friction measurements are available using the Robertson and Wride (1998) method. Using this method, 14 liquefaction and no liquefaction cases (16%) are misclassified. Additionally, no cases from the higher fines content soil groups plot near the base curve, implying that the soil type adjustment based on CPT-only data is overconservative (i.e., too low) at higher fines contents.

Because of the potential issues with using CPT-only methods to estimate liquefaction resistance (Newman et al. 2006), the authors recommend that the fines content adjustment presented in Equation (1) be used with the following numerical form of the Soil Group 1 liquefaction resistance relationship (i.e., "clean sand base curve" plotted in Figure 3(a):

$$\begin{aligned} SRR = 0.10 \leq \quad & -0.4695 + 0.3357 q_{c1cs} - 0.08342 q_{c1cs}^{\ 2} + 0.01062 q_{c1cs}^{\ 3} \\ & -0.0006641 q_{c1cs}^{\ 4} + 0.00001638 q_{c1cs}^{\ 5} \leq 0.45 \end{aligned} \tag{3}$$

where SRR is the seismic resistance ratio (i.e., the stress ratio on the liquefaction resistance curve). While this equation combined with the fines content adjustment in Equation (1) allows the calculation of liquefaction resistance to be automated in a spreadsheet or other computer application, care should be taken to ensure that the results are reasonable. If the calculated SRR is outside of the range specified in Equation (3) then SRR should be determined visually. The SRR can be compared to the value of SSR (calculated as described by Youd et al. (2001)) to determine a factor of safety against liquefaction.

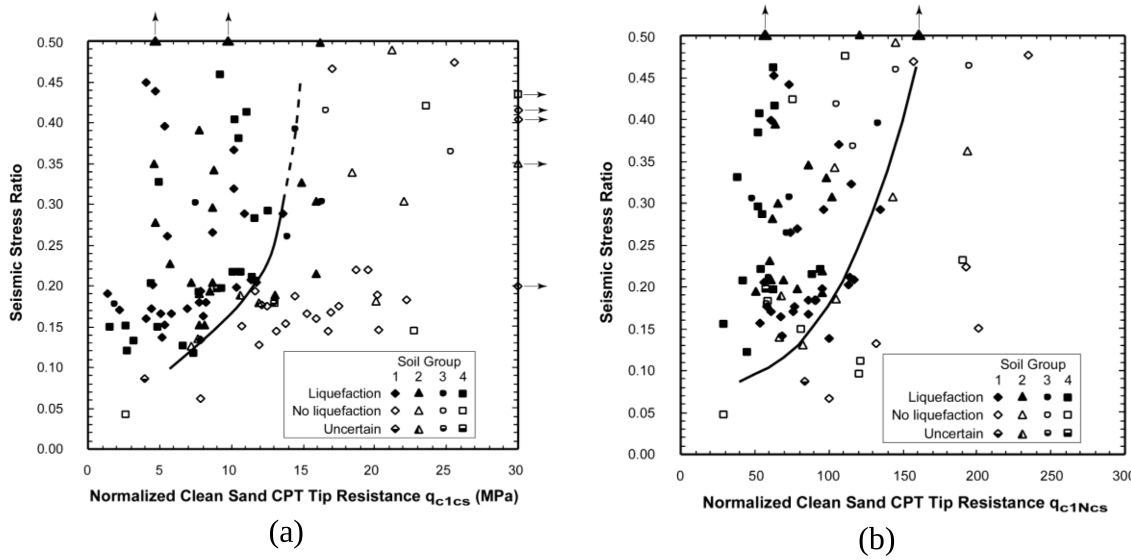

Figure 3. Comparison between data adjusted for soil type using (a) fines content adjustment developed herein and (b) using CPT-only method of Robertson and Wride (1998)

Conclusions

A refined database of 117 liquefaction and non-liquefaction case histories using the proposed stringent selection criteria described herein are used to develop new liquefaction resistance relationships. In addition, the proposed liquefaction resistance relationships use four Soil Type Groups instead of the three groups utilized by Olson and Stark (1998) as well as directly-measured fines content. Using the proposed liquefaction resistance relationships, a fines content adjustment is developed. This adjustment and the "clean sand" liquefaction resistance relationship (for Soil Group 1) are presented in numerical form to facilitate their use.

Standard penetration tests performed adjacent to the cone penetration tests allow samples to be recovered from critical layers identified during the CPT program. The use of these soil samples, when available, assists greatly in evaluating the susceptibility of a soil deposit to liquefaction during an earthquake. The proposed relationships allow engineers to fully utilize all of the information at their disposal to evaluate the liquefaction resistance of natural soils.

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